VORTEX DYNAMICS IN STRONGLY ANISOTROPIC HIGH-TEMPERATURE SUPERCONDUCTORS

Theses of Ph.D. dissertation

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Introduction

High-temperature cuprate superconductors were discovered by Georg Bednorz and Alex Müller in 1986. The discovery has induced an enthusiasm rarely seen in the history of physics not only in physicists, but in the general public as well. Although this was caused by the (ever since unfulfilled) vision of room-temperature superconductors, the discovery opened many new, thence unclosed chapters in solid state physics. Today, when we have already learnt to use these materials in practice, we still do not understand well the dissipative mechanisms that limit applications.

In most technical applications of Type-II superconductors the strong magnetic field induced by the large current flowing inside the superconductor is used. In contrast to common belief, it is not the upper critical field that delimits zero-resistance conduction, but the movement of vortices that are induced by the magnetic field. The possibility of dissipation caused by the vortex-flow has arisen not long after the discovery of vortices – based on the analogy with superfluid helium. This dissipation is caused by the core of the vortex that contains normal electrons. For conventional superconductors Bardeen and Stephen has shown that the resistance caused by the flow of vortices is proportional to the magnetic field, and at the upper critical magnetic field it reaches the resistance of the normal phase. Many have inspected the validity range of the Bardeen-Stephen law for high-temperature superconductors, but the match was not definite. The sceptic standpoint is reinforced by the fact that in high-temperature superconductors the order parameter has *d*-wave symmetry, has nodes in certain directions, so the spectrum of quasi-particle excitement has significant differences compared to conventional superconductors.

The discovery of high-temperature superconductors has enriched the otherwise complex question with several new elements. Due to the very anisotropic and layered structure of these materials completely different dissipation mechanisms must be taken into account inside the superconducting layers as in the direction perpendicular to them. Also because of anisotropy several research projects have been concerned with the dimension of the vortex system.

In the liquid phase of the high-temperature superconductors many have examined the Hall-effect caused by the vortices. However, in the vortex solid phase – partly due to technical reasons – the Hall-effect could not be shown. At the same time, it is known that elastic and periodic 2D systems interacting with defects in random positions move along channels after bursting from the fixtures. Leaving the channels, and thus reaching really free flow, needs an even greater force. In this case, the coerced movement along the channels prevents the Hall-effect. Due to this, it may be reasonable to use larger driving currents in the vortex solid phase when looking for the Hall-effect.

Most of my experiments were conducted in the Research Institute for Solid State Physics and Optics of the Hungarian Academy of Sciences, where the research in high-temperature superconductors has a 20 year old tradition. Beyond that, I had the opportunity to work in France, in the laboratory of F. I. B. Williams (Saclay, CEA, SPEC).

Goals

During my doctoral work, I was occupied with the experimental examination of dissipation occurring in strongly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) single-crystals in case of large transport currents and large magnetic field.

Formerly, our research group has shown that on the temperature – magnetic field phase diagram of the vortex system in the vortex solid phase there exists a metastability line, below which, contrary to previous opinions, the field cooled sample is less stable than the sample cooled without a field [B. Sas *et al.*, Phys. Rev. B, 2000]. My goal was to comprehend the nature of this phase line. Due to this, I also extended my measurements to underdoped samples, examining the effects of perturbations caused by magnetic field, temperature and transport current.

As in BSCCO single-crystal samples, due to their strongly anisotropic electric properties, the intra-planar and inter-planar dissipative processes always occur simultaneously, thus it is important to determine the shape of the dissipative range. Consequently, we needed samples that had "steps" of different depth carved into them and thus made it possible to measure the voltages appearing inside conducting planes in different depths.

In vortex liquid phase, I have examined the dissipation due to vortex movement in the large-current extreme case. From the experiments previously performed by our group, it could be seen that the Bardeen-Stephen law observed in conventional superconductors is not valid for BSCCO single-crystal samples. I have attempted to uncover the reason for this and to interpret the results of the measurements.

Previously, no Hall-voltage could have been detected in the vortex solid phase. Using the possibility given by the large applied transport current I tried to show the Hall-effect in this phase.

Research methods

The BSCCO bulks needed for the experiments were produced in the laboratory of László Forró (EPFL, Lausanne), using a continuously controlled melt cooling technique. The splitting and contacting of samples were made mostly in Debrecen (ATOMKI), and Lausanne. Rectangular and optically smooth samples were split from the bulks, and were heat-treated at 900 K in flowing oxygen for two hours. The goal was to optimise and stabilise oxygen doping. For the doping of underdoped samples, praseodymium was used, which is built in the place of potassium.

Measurements were made using the Magnetic Property Measurement System (MPMS-5S) manufactured by Quantum Design. This contains the cryostat, the superconducting magnet, the system regulating the temperature and the magnetic field, and the SQUID detector. The instrument was controlled using a computer.

I examined the dynamics of vortex systems mainly using transport measurements, with short-pulse large-current pulse-technique specially developed for this measurement. I studied the critical current where dissipation occurs and the dissipation itself above the critical current in a wide magnetic field and temperature range. Most of my conclusion were drawn by analysing the current–voltage characteristics in the large current range.

I complemented the transport measurements with other investigations, with magnetic measurements among others. I examined the electron concentration effect of the superconducting layers using alloying. For the better interpretation of my transport measurements, I also studied samples with special shape and contact arrangements. For some samples we carved terraces with a depth of a couple of hundred nanometres in the whole length of the sample. These specially shaped samples were manufactured in the Saclay laboratory (SPEC, CEA, Saclay).

For interpreting the current distribution and the dissipation occurring for large currents, I used numeric modelling.

New scientific results

1. I have shown that similarly to the optimally doped BSSCO high-temperature superconducting single-crystals the phase diagram of the strongly underdoped single-crystals also contains a so-called T_{ms} metastability line. For underdoped samples, the field-cooled (FC) samples under this T_{ms} temperature can be transferred to stable zero-field-cooled (ZFC) state not only using magnetic perturbation, but also using current perturbation. The ZFC state however shows irreversibility with respect to temperature change. Crossing the metastability line, the exponent describing the dependence of the critical current on the magnetic field changes suddenly due to a change whether in a change in the temperature or a change in the magnetic field. Metastability hints at a dynamic transition, while the change in the exponent of field–dependence hints at a primary phase transition. I examined both possibilities and I showed that the dynamics model gives a sufficient answer to the above described phenomenon. In the model, the metastability line means the beginning of thermal detachment of the traps that fix the vortices and gives a $\log H \propto 1/T_{\mathrm{ms}}$ dependence, which fits well with the measured data in both cases of doping.

2. On high-precision steppedly milled samples I performed a flux-transformer measurement at low temperatures and in magnetic fields smaller than the fields corresponding to the 2D–3D transition of the vortex system, where the vortex system is three-dimensional. From the small-angle neutron scattering experiments we know that 3D vortex structure forms in FC case. Contrary to this, I got identical critical current on the surface of the sample and on the surfaces of the steps in different depths of the sample in samples prepared in ZFC way. However, in the case of FC preparation, the two critical currents were different.

   Using a current distribution model, I have shown that the dissipation in high-temperature superconductors is determined not by the dimension of the vortex system but the current distribution formed due to the strong anisotropy.

3. I re-analysed the high-current transport measurements on BSSCO single-crystals preformed previously by our group. The differential resistance of the sample tends to a constant in case of currents many times exceeding the threshold of thermal loss. The temperature and magnetic field dependence of this high-current resistance was the object of my analysis.

   I have shown that the high-current R_{f} resistance of the single-crystal samples in the vortex liquid phase measured by contacts placed on the well-conducting *ab* plane scales with the H_{c2} upper critical magnetic field. By scaling I mean that on different temperatures the resistances measured for identical H/H_{c2} values are identical, thus $R_f = f(H/H_{c2})$, where H is the magnetic field, and the function f is independent of temperature. I have shown that the shape of the f function is $f = R_n[1 + \alpha \log(H/H_{c2})]$, where R_n is the sample's normal resistance at the T_c critical temperature and $\alpha = 0,20 \pm 0,03$. I pointed out that, as the current–voltage curve gets linear close to the critical temperature, in this range previously precisely circumscribed with my colleagues it is possible to make comparisons with the precise small-current measurements found in literature.

I have analysed the small-current data of Busch and his colleagues [R. Busch *et al.*, Phys. Rev. Lett., 1992] and I have shown that they quantitatively match the scale law I set up ($\alpha = 0,23$). By analysing these same small-current data, I have shown that the resistivity in the *ab* plane is $\rho_{ab} = \rho_{ab}^{n}(H/H_{c2})^{\beta}$, where ρ_{ab}^{n} is the resistivity in the normal phase, and for the β exponent I got 3/4, which is different from the $\beta = 1$ exponent observed in conventional superconductors described by the Bardeen-Stephen law.

Using the above relation and the scale law for R_f I got an analytic form for the ρ_c resistivity in direction c, which fits well for the measurement results that can be found in literature. My analysis for the magnetic resistance in the c direction has a good fit with the previously described and well-studied maximum in magnetic resistance; in my model this is a natural consequence of the density of states increasing with the field and the decreasing tunnelling probability. I pointed out that the above description loses its validity in the vortex solid phase, most probably due to the change in the spatial correlation between pancake vortices.

4. I have shown that in the case of sufficiently large driving currents the Hall-effect appears also in the vortex solid phase. With this, I have proven that the vortex lattice moves in the potential field caused by random defects, similar to other two-dimensional elastic lattices, along channels after tearing down from the fixtures. Leaving these channels needs a new, even greater critical current; using a larger current the vortices really move freely. According to my results, leaving the channels needs five times greater force than tearing down the vortices.

Scientific publications connected to the thesis

Foreign language (non-Hungarian) article in international journal

Á. Pallinger, B. Sas, G. Kriza, K. Vad, L. Forró, H. Berger, F. Portier, F. I. B. Williams
Metastability of two-dimensional vortex glass in $Bi_2Sr_2CaCu_2O_{8+\delta}$
Physical Review B **80**, 024206 (2009)

Á. Pallinger, B. Sas, I. Pethes, K. Vad, F. I. B. Williams, G. Kriza
Breakdown of the Bardeen-Stephen law for free flux flow in $Bi_2Sr_2CaCu_2O_{8+\delta}$
Physical Review B **78**, 104502 (2008)

International conferences

Á. Pallinger, B. Sas, G. Kriza, F. I. B. Williams, L. Forró
Hall effect of vortex solid phase in BSCCO (előadás)
GDR 2284 – systèmes élastiques en potentiel désordonné
Vogüé, France, 2005

Á. Pallinger, B. Sas, G. Kriza, F. I. B. Williams, L. Forró
Channeling effects in the transport properties of high T_c monocrystalline BSCCO (poszter)
Vortex Wroclaw 2006, The 11th International Workshop on Vortex Matter
Poland, 2006

Miscellaneous scientific publications

I. Pethes, A. Pomar, B. Sas, G. Kriza, K. Vad, Á. Pallinger, F. Portier, F. I. B. Williams
Potential and current distribution in strongly anisotropic $Bi_2Sr_2CaCu_2O_8$ single crystals at current breakdown
Phys. Rev. B **68**, 184509 (2003)

K. Vad, J. Hakl, A. Csik, S. Mészáros, M. Kis-Varga, G. A. Langer, Á. Pallinger, M. Bodog
Application of Secondary Neutral Mass Spectrometry in the investigation of doped perovskites
Vacuum **84**, 144 (2010)

G. KRIZA, Á. PALLINGER, B. SAS, I. PETHES, K. VAD, F. I. B. WILLIAMS
Bardeen-Stephen flux flow law disobeyed in $Bi_2Sr_2CaCu_2O_{8+\delta}$
Physica B **404**, 510 (2008)